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Energy and Environment

# Accelerators for Fusion Energy

Fusion is potentially a clean and safe energy source. Inertial fusion energy (IFE) has different challenges from magnetic fusion. Among them are the pulsed nature of the energy production, the required high rate of target production and target placement in the reactor chamber, and the reactor driver interface [1]. There are three main types of inertial fusion drivers: laser beams, ion beams, and Z-pinches. In all inertial fusion energy (IFE) concepts, the driver and the reactor chamber are separate, which leads to savings in cost, improved access, ease of maintenance, and reduced concerns for safety and radiation contamination. We focus here on the case for a vigorous accelerator and beam research program toward inertial fusion energy driven by heavy ion beams.

For ion-driven fusion, the choice of accelerator has very significant consequences for the achievable energy gain and the overall efficiency of an ion-driven IFE system.
Heavy ions of mass >100 amu and ion kinetic energy above ~1 GeV have the correct stopping range to drive fusion targets. Such beams have $\beta \approx 0.1$-$0.2$, so are amenable to acceleration as relatively long bunches, and then compressed longitudinally to achieve the required short bunch (2-20 ns) on the fusion target within a radius of a few millimeters. Two main approaches to heavy ion drivers have been studied: RF accelerators because of the extensive experience with them in high energy and nuclear physics, and induction accelerators, because of their unusually high efficiency for high beam current. The US has focused on induction accelerators for HIF. Since the beams are space charge dominated, the transverse focusing force must balance the space charge force. Multiple beams are necessary (to subdivide the tens of kA impinging on the target to a few kA) to meet the focal spot requirements and to achieve a beam current compatible with superconducting magnets. The multiple beams can be accelerated simultaneously through the same induction cells, and this combined with superconducting magnets can produce overall accelerator efficiencies of ≈20%.

The advantages of heavy ion fusion (HIF), identified in many past DOE reviews [2], still apply now:

- Accelerators with total beam energy of ≥ 1 MJ have separately exhibited intrinsic efficiencies, pulse repetition rates (>100 Hz), power levels (TW), and durability required for IFE.

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* http://www-afrd.lbl.gov/fusion.html The HIFS-VNL collaboration includes LBNL, LLNL, PPPL.

- Thick-liquid wall protected target chambers are designed to have 30-year plant lifetimes. These designs are compatible with indirect-drive target illumination geometries, which will be tested in NIF experiments. Thick-liquid protection [3] with molten salt having high thermal and radiation stability (LiF-BeF2, or flibe) has been a standard aspect of most HIF power plant concepts in the past ≈20 years.
- Focusing magnets for ion beams avoid most of the direct line-of-sight damage from target debris, neutron and γ radiation. Thus, only the final focusing magnet coils need to be hardened or shielded from the neutrons (diminished flux due to the thick liquid protection).
- Heavy ion fusion power plant studies have shown attractive economics and environmental characteristics (only class-C low level waste) [4]. Accelerator design efforts have converged on multiple heavy ion beams accelerated by induction acceleration. After acceleration to the final ion kinetic energy, the beams, which are non-relativistic, are compressed axially to the 4-30 ns duration, (few-hundred TW peak power) required by the target design. Simultaneously they are focused to a few millimeter spot on the fusion target.

Furthermore, there is a desire to resolve fuel cycle issues for increasing the role of nuclear energy. The recent Laser Inertial Fusion-Fission Energy (LIFE) initiative that builds upon NIF ignition, is likely to rekindle national interest in developing intense, high power ion beam accelerators for fusion energy production and for fusion-fission hybrid concepts that combine an ion beam driven fusion neutron source with a fission blanket. While serving as a carbon-free energy source, hybrids offer the enormous potential benefit of transmuting the long-lived radioactive byproducts of fission-based nuclear reactors, thus dramatically reducing the nuclear waste problem. Systems with sufficiently efficient neutron sources to achieve deep or complete burn-up would eliminate the need for chemical separation reprocessing and make it possible to limit fuel shipments to non-weapons-usable materials, thus achieving a high level of proliferation resistance.

A research and development effort culminating in a credible, integrated design for a HIF based prototype for pure fusion or hybrid fusion and fission would include accelerator and beam physics issues and reactor design and driver interface issues:

- Design fusion targets that are able to give satisfactory yield and gain with lower driver beam energy. Recent target designs aimed at pure HIF show total driver beam energy requirements as low as ≈2 MJ for indirect drive [5] and 0.5 MJ for direct drive [6].
- Reactor design, neutronics, and radioactive material handling: One objective is to attempt to preserve the significant advantage of thick liquid protection of the reactor chamber structural wall.
- The choice of final kinetic energy, ion species, ion acceleration schedule and transverse beam focusing architecture will depend on primarily the target design. Thus, an accelerator research program would include beam physics modeling, smaller-scale experiments, and system studies. The near-term objective of the program will be the design of two facilities:
    - A prototype experimental facility for fusion target experiments integrated with all key ion beam manipulations. Concepts were developed for an experimental

    - facility with similar goals several years ago [7], but should be revisited in light of developments since then.
    - A demonstration power plant design.
- The following cross cutting accelerator and beam physics research topics must be studied further and developed into reliable solutions:
    - High current ion injectors: These must deliver ~1 Ampere level current (if singly ionized), with low emittance. The bunch duration is a few to 20 μsec at 5-10 Hz. Breakthroughs here will benefit research areas requiring high intensity hadron beams.
    - Reliable, high field transverse focusing: solenoids, magnetic quadrupoles, electrostatic quadrupoles [8].
    - Multi-beam induction accelerator module design and single beam induction accelerator design.
    - Electron clouds and beam background gas interactions. This is cross-cutting with e-cloud research in HEP and high intensity accelerators.
    - Axial beam compression and methods to compensate or correct for chromatic aberrations.
    - Beam - plasma instabilities.

This is the right time to take a fresh, comprehensive look at heavy ion driven inertial fusion energy options.

## REFERENCES


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